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Radical innovation in scaling up: Boeing's Dreamliner and the challenge of socio-technical transitions

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ABSTRACT

Radical technological innovations are needed to achieve sustainability, but such innovations confront unusually high barriers, as they often require sociotechnical transitions. Here we use the theoretical perspectives and methods of Science and Technology Studies (STS) to demonstrate ways that existing theories of innovation and sociotechnical transitions, such as the Multi-Level Perspective (MLP), can be expanded. We test the MLP by applying STS methods and concepts to analyze the history of aircraft composites (lightweight materials that can reduce fuel consumption and greenhouse gas emissions), and use this case to develop a better understanding of barriers to radical innovation. In the MLP, "radical innovation" occurs in local niches—protected spaces for experimentation—and is then selected by a sociotechnical regime. The history of composite materials demonstrates that radical innovation could not be confined to "niches," but that the process of scaling up to a wholly new product itself required radical innovation in composites. Scaling up a process innovation to make a new product itself required radical innovation. These findings suggest a need to refine sociotechnical transitions theories to account for technologies that require radical innovation in the process of scaling up from the level of sociotechnical niche to regime.

1. Introduction

On October 26 2011, the Boeing 787 made its first commercial flight on a route from Tokyo to Hong Kong, and set a new standard for fuel efficiency. The 787 "Dreamliner" achieves the highest efficiency among mid-sized airliners by using several innovative technologies, including lightweight composite materials that account for approximately 50% of the aircraft's weight. Launch customer All Nippon Airlines reported that the aircraft is 21% more fuel-efficient than its predecessor. More significantly, Boeing's decision to build the Dreamliner has triggered a broader shift in aircraft manufacturing. As orders for the Dreamliner began pouring in, Boeing's arch rival, Airbus, promised that its direct competitor to the 787, the A350, would boast 53% composite construction (Wall, 2008).

The industry's shift towards composite construction is good news for advocates of energy efficiency, but it also raises a key question: why did the industry not fully embrace these innovative materials earlier? As Fig. 1 shows, airliners have used composite components for decades. Indeed, one business aircraft, the Beechcraft Starship, was built entirely from composites in 1985, and remains operational today, a decade after the manufacturer decided to decommission it (Scherer, 2010). Why has commercial aviation adopted composite materials so slowly, and what policies might enable greater use of weight-saving materials?

By addressing these questions, this paper aims to clarify theories of how technological innovations cross the "valley of death" to enter wide-spread use. As innovation scholars have noted, new innovations may struggle to enter markets, both because they initially have relatively poor performance (Mokyr, 1990 calls them hopeful monstrosities) and because they must be compatible with a broader *sociotechnical regime*—a complex, heterogeneous, and interdependent network of organizations, artifacts, engineering practices, skilled workers, government policies, financing systems and consumers. Such regimes encourage incremental innovations, which improve price and performance of technologies already in the market, while discouraging radical innovations, which are discontinuous and can cause regime change (Freeman and Perez, 1988).

Evolutionary economists initially coined the "regime" concept to describe the rule-sets that govern decisions about how to develop and produce new technologies (Nelson and Winter, 1977, 1982; Dosi, 1982). Regimes encourage what engineer-historian

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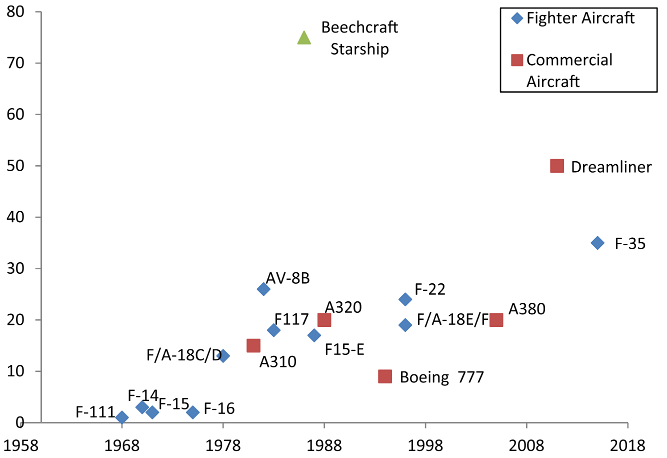

Fig. 1. Percentage of aircraft mass comprised of composite materials (initial configuration).

Walter Vincenti (1993) termed "incremental design," which is based upon known concepts and technologies, rather than "radical design," in which engineers must develop new knowledge as well as new artifacts. Rip and Kemp (1998) expanded the notion of regime to include the rules shared by technology's "selection environment." Geels coined the notion of "sociotechnical regime" to describe a larger set of rules—those held by policymakers, user groups, financiers, and so on (Geels, 2002). This paper defines sociotechnical regimes broadly to include artifacts and organizations, a usage that is common in the literature (see e.g. (Kemp et al., 1998)), and explicit in Gabrielle Hecht's notion of "technopolitical regimes" (Hecht, 2001; Allen & Hecht, 2001).

Regimes can create interdependencies that cause "technological lock-in," a situation in which new innovations are unable to succeed, even if they are superior to established technology (Unruh, 2000; David, 1985; Arthur, 1989). Radical innovations often depend on the integration of many interdependent systems to succeed; although they may be "generic" in their ability to transform many industries and applications, radical innovations can rarely slot into a modular framework in a "plug-and-play" manner (Christensen et al., 2015; Maine and Garnsey, 2006). In particular, downstream obstacles in the value chain often need resolving before adoption can take off (Musso, 2009). Future improvements in such radical innovations are hard to predict when those innovations are still immature, and may not follow the traditional 'learning curve' seen in more mature technologies (Linton and Walsh, 2004).

Scholars have developed several frameworks for analyzing how such innovations can be successfully introduced into regimes. Kemp, Schot, and Hoogma proposed creating "strategic niches," protected spaces for technological innovation and experimentation by a broad range of stakeholders, including researchers, companies, policymakers, and end-users of technology (Kemp, Schot and Hoogma, 1998). Rotmans, Kemp, and van Asselt broadened the notion of niche management to overall transition management (Rotmans et al., 2001).

Thinking about transitions has also been heavily influenced by the multi-level perspective (MLP), which treats sociotechnical *regimes* as an intermediate level between local *niches* and overarching *landscapes* (Geels, 2002, 2005a, 2006b, 2011, 2014; Elzen and Geels, 2004; Geels and Schot, 2007; Raven and Geels, 2010; Sutherland et al., 2015; Fuenfschilling and Truffer, 2014). According to Geels and Schot (2007, p. 400), "transitions come about through interactions between processes at these three levels: (a) niche-innovations build up internal momentum, through learning processes, price/performance improvements, and support from powerful groups, (b) changes at the landscape level create pressure on the regime and (c) destablization of the regime creates windows of opportunity for niche innovations."

Conceptual frameworks such as strategic niche management and the MLP helpfully broaden evolutionary economic approaches to sociotechnical transitions by emphasizing social and cognitive dimensions of innovation and selection (Geels 2006a, b; Raven and Geels, 2010; Klerkx and Leeuwis, 2008). However, most of the literature focuses on what innovation scholars have dubbed "product innovations," which are associated with new end-products, rather than "process innovations," which improve the performance of existing products (Tornatzky and Fleischer, 1990; Abernathy and Utterback, 1978). Advanced materials, such as the composites discussed here, are examples of process innovations, which have been shown to confront unique challenges for value creation (Maine and Garnsey, 2006; Maine, Lubik and Garnsey, 2012; Linton and Walsh, 2008, 2004)

Furthermore, we argue that transition theories in general, and the MLP in particular, could be refined by more systematically applying methods drawn from science and technology studies (STS). In what follows, we briefly outline three ways in which transition theories could benefit from STS insights. We then use these methods to analyze the development of a "niche" for composite aircraft components, and efforts to scale up that niche to a potentially regime-changing aircraft—the Dreamliner. Whereas the sociotechnical transitions literature generally argues that radical innovations are developed in niches, and subsequently selected by the dominant regime, this case study shows that some technologies must undergo radical innovation in the process of scaling up from the niche to regime level. We argue that STS methods and concepts can help the transitions literature to accommodate the need to take radical innovation beyond the niche.

2. Methods and theoretical perspective

Like many studies of sociotechnical transitions, we adopt a case study method, using the history of composites development and Boeing's Dreamliner experience to extend and refine existing theories. However, our approach is different than most existing studies in three ways which reflect the theoretical perspective and methods of STS.

First, while sociotechnical transitions theory has primarily been developed through case studies of innovations that successfully effected transitions, we focus on a partial or incomplete transition. This contributes to a theoretical perspective that follows the STS 'symmetry principle,' in which success and failure both require sociological explanation (Pinch and Bijker, 1987). Although there are a few case studies of innovations that have yet to cause transitions (Hofman and Elzen, 2010; Elzen et al., 2011; Grünewald et al., 2012; Raven and Geels, 2010; Geels, 2014), frameworks such as the MLP have primarily been used to study successful transitions (Bunduchi et al., 2011; Turnheim and Geels, 2012; Hall et al., 2014; Geels, 2005b, 2002, 2006a; Geels and Schot, 2007; Berggren et al., 2015; Rosenbloom and Meadowcroft, 2014). Geels and Schot (2010, p. 79) note that theorization would be improved by correcting 'the bias towards winners and novelty'. Similarly, Wells and Nieuwenhuis (2012) argue that the literature focuses on causes of change at the cost of understanding "transition failure."

Second, rather than pre-defining composite aircraft components as either "incremental" or "radical" innovations, we focus on how different types of actors in the commercial aviation regime have conceptualized these innovations. This methodological choice reflects the STS emphasis on the interpretive flexibility of technology (Pinch and Bijker, 1984). Different actors could view the same innovation as relatively radical or conservative,

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